Dynamical nonlinearity in the atmospheric response to Atlantic sea surface temperature anomalies

Walter A. Robinson,[1] Shuanglin Li,[2] and Shiling Peng[2]

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[1] Large ensembles (100 members) of atmospheric general circulation model experiments are forced throughout the Northern Hemisphere cold season by four different sea surface temperature (SST) fields: the observed climatology, the so-called SST tripole pattern, and its tropical and its extratropical subcomponents. Late winter responses to these anomalies are of modest amplitude, in comparison with the amplitudes of climatological stationary waves, but are, because of the large ensemble, significant. Despite their modest amplitudes, the responses display additive nonlinearity, in that the sum of the separate responses to the component anomalies differs significantly from the response to the tripole. Neither the heating field nor the basin averaged zonal winds display this nonlinearity. It is most evident in a sub-basin scale wave train, and most significant in its impact on the amplitude of the geopotential response. These results indicate that even for modest forcing, responses to patterns of SST anomalies cannot necessarily be understood as the sums of responses to constituent anomalies. *INDEX TERMS:* 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3319 Meteorology and Atmospheric Dynamics: General circulation; 3367 Meteorology and Atmospheric Dynamics: Theoretical modeling. **Citation:** Robinson, W. A., S. Li, and S. Peng, Dynamical nonlinearity in the atmospheric response to Atlantic sea surface temperature anomalies, *Geophys. Res. Lett.*, *30*(20), 2038, doi:10.1029/2003GL018416, 2003.

1. Introduction

[2] It is expected that the dynamical responses of the atmosphere to weak forcing are approximately linear, such that the response to a forcing of one sign is complementary to that of the opposite sign, and such that the sum of the responses to multiple forcings equals the response to the sums of those forcings. Despite their modest amplitudes, however, modeled atmospheric responses to tropical and extra-tropical Atlantic sea-surface temperature anomalies have displayed perplexing nonlinearity [*Kushnir et al.*, 2002]. Previous studies revealed asymmetry of the responses with respect to sign [“sign nonlinearity”, *Pitcher et al.*, 1988; *Kushnir and Lau*, 1992; *Peng et al.*, 2002, 2003], and with respect to the makeup of the anomaly [*Sutton et al.*, 2000]. The latter, denoted “additive nonlinearity” is the subject of this note. Additive nonlinearity is the property that when an anomaly pattern is broken down into two constituent parts, the sum of the responses to those parts does not equal the response to the whole. While *Sutton et al.* [2000] found additive nonlinearity in the responses to Atlantic SST anomalies similar to those considered here, questions remain. Has the nonlinearity been revealed with statistical confidence, or is it merely the statistical artifact of insufficiently sampling a noisy signal? Here we present results of experiments with sufficiently large ensembles of model runs—100 members—that the presence of substantial additive nonlinearity is identified with confidence (*Sutton et al.* used 8-member ensembles). If the nonlinearity is real, what is its dynamical source? It is often assumed that the answer lies in the fluxes of latent and sensible heat across the sea surface, since even simple treatments of these fluxes, such as bulk formulae, have “built-in” nonlinearity resulting from the quasi-exponential dependence of saturation vapor pressure on temperature and from the multiplicative dependence of fluxes on the surface wind speed. Here the nonlinearity is traced to the large-scale dynamics of the response.

[3] The atmospheric general circulation model experiments are described in the next section, and results are presented that clearly demonstrate additive nonlinearity. Diagnostic calculations intended to isolate the source of the additive nonlinearity are described in section 3, and section 4 summarizes the results and discusses their possible dynamical mechanisms and implications.

2. Experiments and Results

[4] The basic ensemble of experiments is that described by [*Peng et al.*, 2002, 2003] (henceforth PRL1 and PRL2). Ensembles, 100 members each, of control and SST anomaly runs are carried out for the Northern Hemisphere cold season, September to April, using either observed climatological sea-surface temperatures, or the climatology with an anomaly added. This anomaly, displayed in Figure 1, is denoted the negative tripole pattern. The tripole anomaly used here is found by linear regression of the SST against the leading empirical orthogonal function (EOF) of Northern Hemispheric variability in the atmosphere (PRL1), and it closely resembles the leading EOF of North Atlantic SST, the pattern used by *Sutton et al.*. Here we focus on the atmospheric response to this pattern and to its constituent anomalies, in late winter, February to April, because it is for this sign of the anomaly and for this season that our model produces the most robust responses (PRL1, PRL2). Two additional 100-

[1]Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign, USA.
[2]NOAA-CIRES Climate Diagnostics Center, USA.

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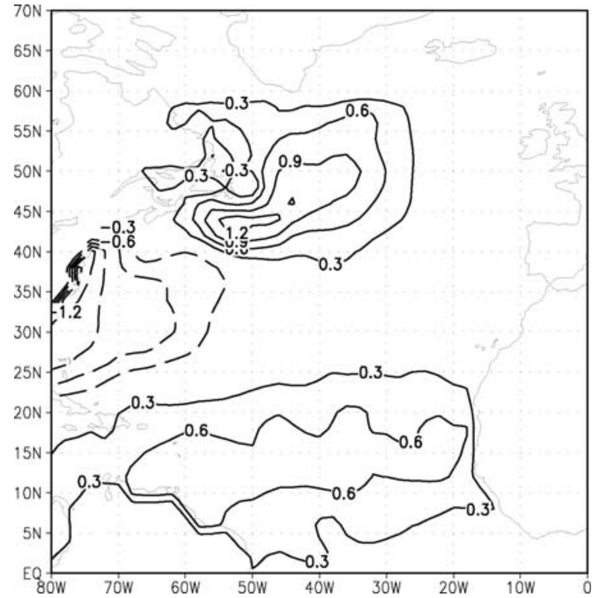

Figure 1. SST anomaly – the ''negative tripole'' – used in these experiments. The southernmost positive anomaly is the tropical monopole, and the remainder of the pattern comprises the midlatitude dipole. The contour interval is 0.3°C, negative contours are dashed, and the 0°C contour is omitted.

member ensembles are carried out for the present study: one, with only the southernmost positive SST anomaly applied, denoted the tropical monopole, and the other, with the remainder of the tripole applied, denoted the midlatitude dipole. In each case the ''response'' for any field is defined as the difference between the averages of that field over the ensemble for a particular SST anomaly and over the control ensemble.

[5] Figure 2 shows the basic result. The first panel displays the response in 500 hPa geopotential heights to the entire SST tripole. The SST anomaly (Figure 1), with a maximum amplitude of 1.2°C produces a geopotential height response at 500 hPa with a maximum strength of about 30 m. This is a small-amplitude signal, in comparison with the strength of the climatological stationary waves over the Atlantic, ~160 m, or with the poleward decrease of heights from the subtropics to the polar regions, ~500 m. Figures 2b and 2c similarly show the responses to the tropical monopole and to the midlatitude dipole anomalies. Figure 2d shows that these results do indeed display additive nonlinearity. What is displayed is the difference between the tripole response and the sum of the tropical monopole and midlatitude dipole responses. If the responses were linear, this quantity would vanish everywhere, but it does not. The shading indicates where this quantity is significantly different from zero with 95% confidence. Strong nonlinearity (~50%) is seen in the region of high geopotential heights south of Greenland, though there are broad regions of significant additive nonlinearity throughout the Atlantic sector. The net effect of this additive nonlinearity is to substantially increase the negative NAO response to the negative tripole SST anomaly, a result consistent with that obtained by *Sutton et al.* [2000]. (''NAO'' refers to the North Atlantic Oscillation – the

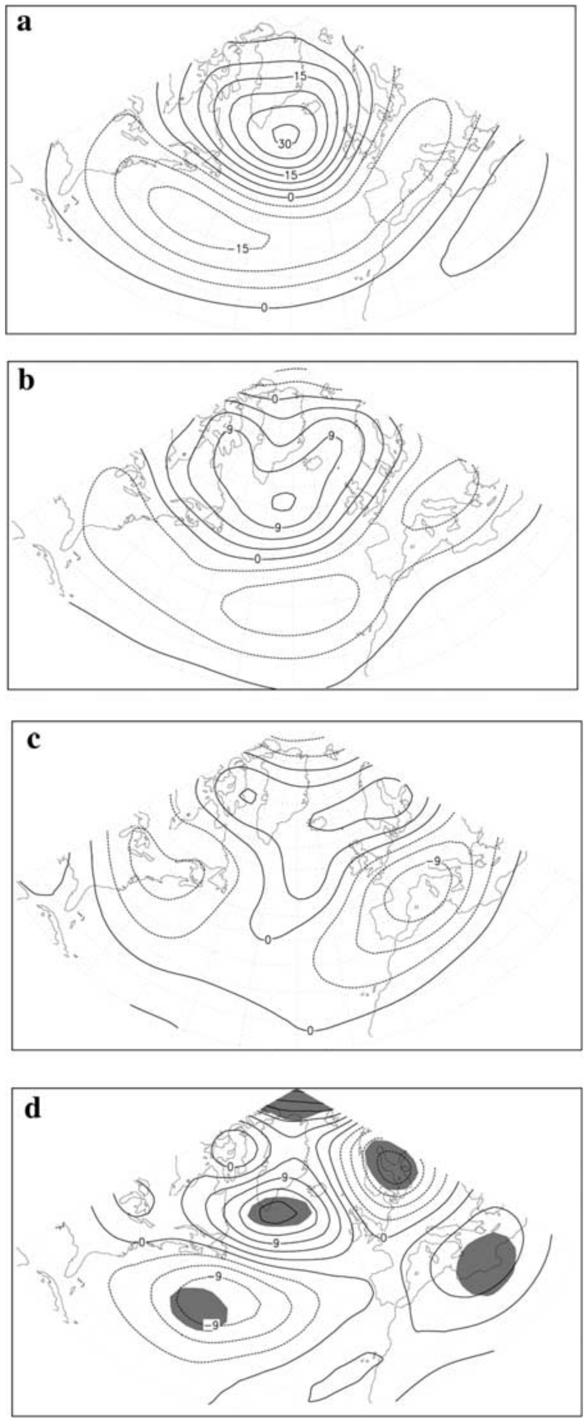

Figure 2. The modeled ensemble average atmospheric response at 500 hPa to the SST anomaly shown in Figure 1. (a) The response to the full tripole. (b) The response to the midlatitude dipole. (c) The response to the tropical monopole. (d) The response to the tripole minus the sum of the responses to the dipole and the monopole. The shading shows where this quantity is significant at the 95% level. The contour interval is 5 m for (a), and 3 m for (b), (c), and (d).

leading EOF of sea level pressure over the North Atlantic; cf. *Hurrell et al.* [2003].)

3. Diagnoses

[6] As mentioned in the introduction, the anomalous diabatic heating, sensible and latent, resulting from the SST anomaly is a plausible source for the nonlinearity of the response. This is not, however, borne out by our results. Figure 3 shows the vertically integrated atmospheric heating resulting from the tripole anomaly (Figure 3a) and the sum of the heating resulting from the tropical monopole and from the midlatitude dipole (Figure 3b). The separate heating anomalies that comprise this sum are strongly localized over their associated SST anomalies. The two panels of Figure 3 are nearly identical. Their differences are nowhere significant at the 95% level. These two heating fields are equally similar when displayed in vertical cross-section (not shown). There is, therefore, no significant additive nonlinearity in the strength of the heating or in its vertical structure. The nonlinearity in SST responses, therefore, cannot be attributed to the nonlinearity intrinsic to atmospheric thermodynamics or to air-sea fluxes.

[7] The geopotential response to the full tripole (Figure 2a), but much less so to either the monopole or dipole alone (Figures 2b and 2c), is zonally elongated across the Atlantic basin, and it projects strongly on the model's NAO pattern, which in late winter closely resembles that in observations. This NAO pattern has a much larger zonal scale than either

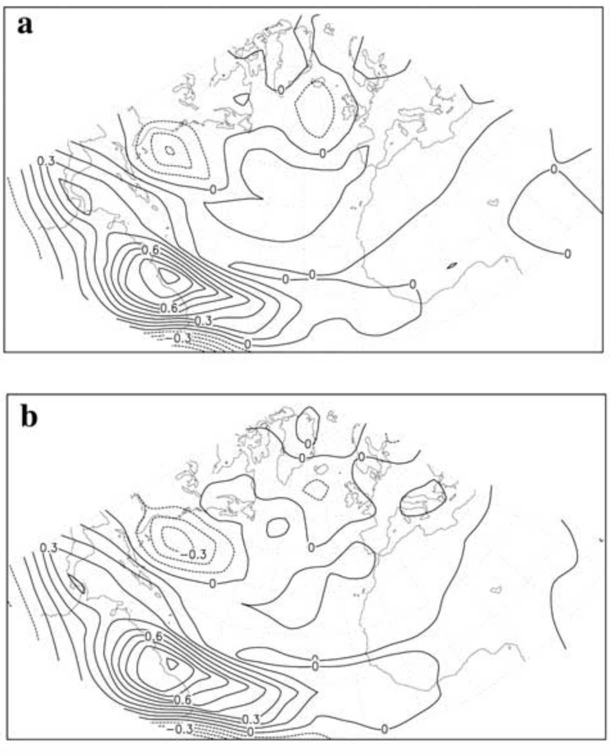

Figure 3. Vertically integrated atmospheric heating anomalies for (a) the tripole and (b) for the sum of the monopole and dipole ensembles. The contour interval is 0.1°C/day and negative contours are dashed.

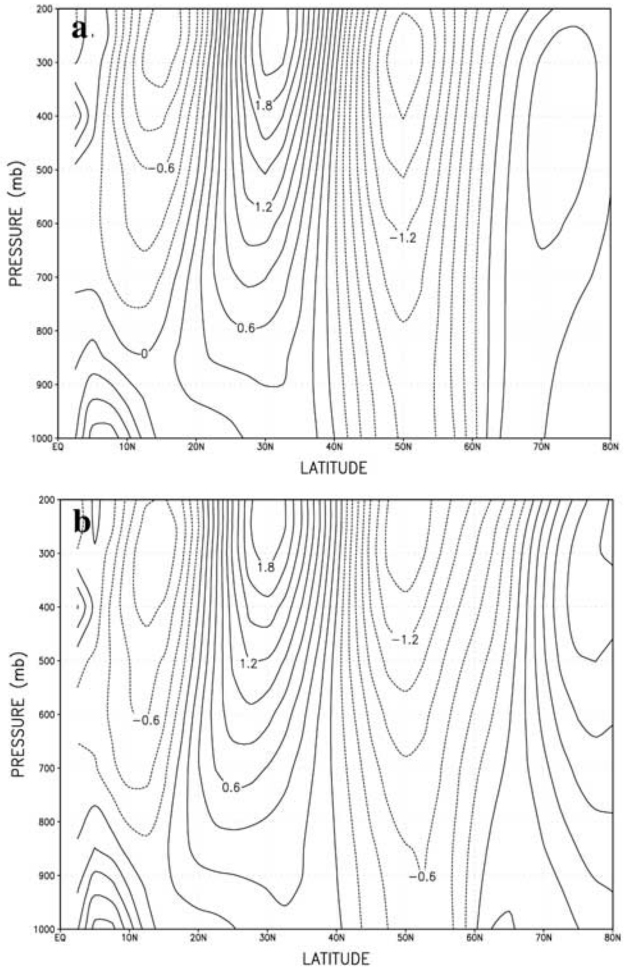

Figure 4. Latitude-height cross-sections of the anomalous geostrophic zonal winds, averaged from 90°W to 30°E for the (a) tripole ensemble and (b) for the sum of the responses to the tropical monopole and midlatitude dipole. The contour interval is 0.2 m s^{-1} and negative contours are dashed.

the SST anomaly or the resulting atmospheric heating anomalies, especially outside of the tropics. In fact, as shown by PRL2, this pattern is primarily driven by transient-eddy momentum fluxes. It might be expected, because the zonally elongated part of the response depends on interactions with transient eddies, that this would be the seat of the dynamical nonlinearity. In fact, the opposite is true. Somewhat arbitrarily, we define the zonal part of the response as a sector average from 90°W to 30°E. Figure 4 displays, in cross-section, the anomalous sector-averaged geostrophic zonal winds for both the full tripole and for the sum of the monopole and the dipole. Again, these figures are very similar, and, as for the heating, their differences are nowhere significant at the 95% level. In high latitudes, where the differences are largest, the variability within each ensemble is also large. Significant differences do appear, however, when we examine the deviations from these sector averages. These are shown in Figures 5a and 5b, again for the full tripole and for the sum of the dipole and monopole experiments. Thus, it appears that the dynamical nonlinear-

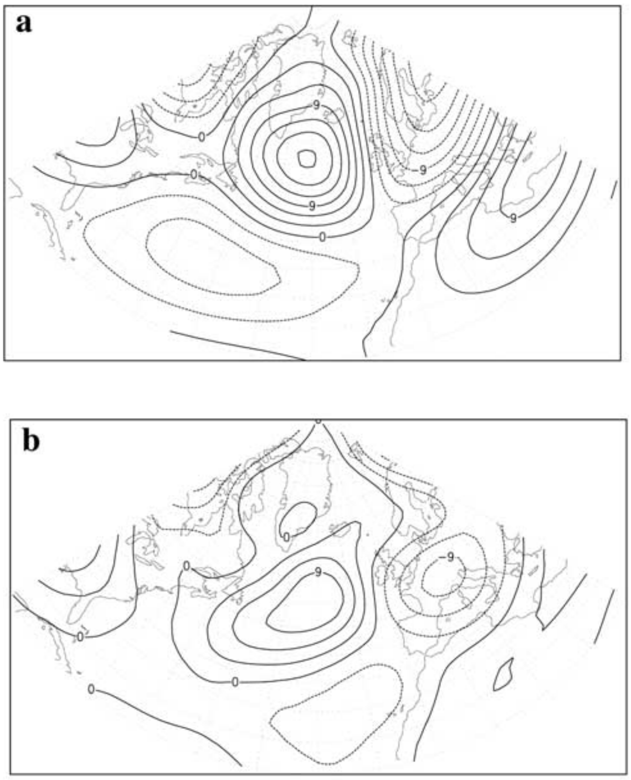

Figure 5. Anomalous 500 hPa heights with the sector zonal average removed: (a) the response to the SST negative tripole. (b) the sum of the responses to the midlatitude dipole and to the tropical monopole. The contour interval is 3 m, and negative contours are dashed.

ity resides in the behavior of sub-basin scale wave trains generated by surprisingly linear heating anomalies.

4. Discussion

[8] Our experiments expose, with some statistical confidence, the presence of additive nonlinearity in the atmospheric response to an Atlantic SST anomaly. This nonlinearity is most prominent in the local deviations from sector zonal averages. Statistically significant nonlinearity is absent from the anomalous heating and from the sector-averaged zonal flow. This result is surprising, because the behavior of local wave trains might be thought to be that part of the response most likely to behave linearly. That this is not the case raises the question of the dynamical basis for this nonlinearity. This is not a question we can answer definitively, but two possibilities come to mind. One is that the transient-eddy feedback on the SST generated anomalous flow is nonlinear. This is not supported, however, by the fact that the component of the response most influenced by transient eddy feedback, the sector zonal averages, is rather linear. Moreover, diagnostic calculations of the transient-eddy feedback, month by month over our many model experiments—those described here plus an additional set of ensembles for the positive tripole—do not reveal statistically significant nonlinearity in the transient-eddy feedback.

[9] A second possibility comes from considering the sector zonal mean as a basic state on which the deviations from that sector mean propagate. If these stationary eddies depend nonlinearly on their basic state, this would explain our results. We might expect small changes in the zonal basic state to effect only small changes in eddy behavior. This expectation, however, is violated in the vicinity of critical lines. The climatological sector averaged zonal winds are westerly at the equatorial tropopause and also throughout the upper troposphere north of 15°N, with a small ($\sim$2° of latitude) intervening gap of weak easterlies. This easterly gap is strengthened and widened by the zonal wind anomalies induced by the tropical monopole SST anomaly. Thus, a plausible, if unproven, mechanism to explain the dynamical nonlinearity displayed in the present results is that through enhanced critical layer reflection—a fundamentally nonlinear process–changes in the sector averaged tropical zonal flow induced by the tropical heating have a substantial and nonlinear influence on the behavior of eddies within the sector.

[10] Finally, what is the significance of these results? First, it has been shown, in contradiction to conventional wisdom, that diabatic heating need not be the source of nonlinearity in responses to SST anomalies. More generally, in clearly exposing the presence of additive nonlinearity and in thus confirming, using very large ensembles, the results of *Sutton et al.*, the present results point up the dangers of conceptual models of responses to atmospheric forcing, even of modest strength, that assume the response is equal to the sum of its parts. The response of the atmosphere to tropical and extratropical forcing are not separable; in many cases it may not be meaningful to ask whether a given atmospheric anomaly has been ''caused'' by SST anomalies in middle latitudes or in the tropics.

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W. A. Robinson, Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign, USA. (robinson@atmos.uiuc.edu)

S. Li and S. Peng, NOAA-CIRES Climate Diagnostics Center, USA.